EDESS: AN ELECTROMAGNETICALLY-DRIVEN EXPLOSIVE-SHOCK SIMULATOR

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Abstract

A new series of electromagnetically-driven shock generators called EDESS is being evaluated at the Naval Surface Weapons Center for generating explosive-like shocks. A prototype generator, EDESS-1, has been built and its performance has been evaluated using 1.0 and 2.0 metric ton payloads. Its shock output and overall performance are close to design expectations as predicted from computer-aided analysis of a simple electromechanical model. Presently, a larger generator, EDESS-2, is being built to extend the payload capability to 5.0 metric tons and a homopolar-driven generator, EDESS-3, is being contempla ed for 15.0 metric ton payloads. This paper presents the electromagnetic shock-generation concept and reviews the progress made in developing these heavy payload shock generators.

Introduction

The strong need to improve the combat survivability of surface ship and submarine equipment without the burdens of excessive testing cost or explosive damage to the surrounding environment has prompted a search for alternatives to present-day shock testing methods. Present day methods commonly employ conventional impact shock machines [1, 2] and, for a range of larger-scale naval equipment, floating shock platforms [3] with underwater explosives as the driver. A new electromagnetic shock-generation concept has been proposed and is being studied by means of a series of prototype shock generators EDESS-1, 2 and 3 each capable of impulse-shocking larger payloads. The acronym EDESS arises from electromagnetically-driven explosive shock simulator. EDESS-1 has been successful for 2.0 metric tons (2.0 Mg) payloads; EDESS-2 is presently being assembled for 5.0 metric ton payloads; EDESS-3 is being designed to handle 15 metric tons.

The Shock Generation Concept

The concept consists of generating explosive like shocks in shipboard equipment by means of the magnetic repulsive force between pairs of spiral-pancake magnet coils that are sandwiched between a large reaction mass and the payload under test. The concept is illustrated in Figure 1 which shows a section view of the two single-layered, spirally-wound coils connected in series opposition. When a pulsed current is made to flow into connector A and around the spiral paths of both top and bottom coils to connector B, a large repulsive force is developed between the pair. It is repulsive because the current has been made to flow oppositely in the nearly-touching circular pancakes (+ refers to current flow into the plane of the paper and•to flow out). The driving energy is supplied by the electrostatic energy stored in a capacitor bank, C, shown in Figure 2. When S1 is closed the bank rapidly pulse-discharges into the driving-coil pair. L_A and L_B are the self-inductances respectively of top and bottom coils. The coils are also mutually coupled as measured by the electrical coupling coefficient K. The total resistance of the coil-pair circuit, R, is kept small to achieve high energy transfer efficiency to the inductive pair. As a result the inductive-capacitive circuit current is slowly-damped and oscillatory. The

crowbar switch S2 is commanded to close when the current in the coil-pair reaches its first maximum, thus producing a single output shock pulse by trapping, in the coil-pair, most of the originally-stored capacitive energy. The top profile in Figure 3 shows the single output shock pulse predicted for EDESS-1 by the NET-2 code under these conditions. If S2 is commanded to close later, on the second maximum of current, then the double-peaked shock pulse shown in the middle curve of Figure 3 results. The lower curve is obtained when S2 is not closed and the original energy in the capacitor bank rings back and forth between the capacitor bank and driving coils, producing a multiple-peaked shock output.

The design of a generator to produce a single shock-pulse of desired duration and shock level is particularly straightforward. It is achieved for a given capacitor bank by a suitable choice of driving-coil inductance in the resulting simple inductive-capacitive electrical circuit. Because shipboard and submarine equipment is generally heavy, their centers of mass often are not displaced significantly during the duration of the shock pulse. Under this condition the choice of coil-pair inductance can be based on the simple ringing frequency formula for an underdamped RLC circuit, namely $f = 1/2\pi\sqrt{LC}$. The single shock-pulse duration, T, is then given approximately by $1/f$ or by,

$$T = 2\pi\sqrt{LC}. \tag{1}$$

To achieve a given shock level the instantaneous force, F, exerted by the coil-pair on the payload (and on the reaction mass) is given by,

$$F = -\frac{\partial}{\partial x}\left(1/2\ LI^2\right) = -\frac{I^2}{2}\left(\frac{\partial L}{\partial x}\right) - LI\frac{\partial I}{\partial x}, \tag{2}$$

where I is the instantaneous current flowing in the coil-pair and $\frac{\partial I}{\partial x}$ is the local spacial derivative of the plate separation. The second term in equation (4) can be expressed as $\partial I/\partial x = (\partial L/\partial L)\ (\partial I/\partial L)$ can be shown to be very nearly equal to $-I/L$. Using

$$L = L_A + L_B - 2K\sqrt{L_A L_B} = L_A + L_B - 2M \text{ in (2) and}$$

evaluating the derivative, the instantaneous driving force takes on the form,

$$F = I^2\left(\frac{\partial M}{\partial x}\right) \tag{3}$$

This force, F, is distributed uniformly over the area of the coil-face, thus offering the possibility of easy alignment between the applied force-center and payload mass-center, a problem sometimes not easily avoided with conventional shock machines.

EDESS-1 System Description

The EDESS-1 generator is shown in Figure 4. It consists of two capacitor modules, a set of capacitor-to-driving-coil connecting cables, one pair of 380 mm diameter driving coils, a pneumatically-actuated fall-back catcher and a 13.3 metric ton reaction mass. The complete generator including power supply and controls

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occupies a floor area of 6 x 10 meters. The reaction mass is air-floated to shock isolate the driving coils from the concrete laboratory floor. Each of the capacitor modules contain twenty 15 μF, 20 kV, MLI 33280 capacitors each being capable of pulse-discharge and oscillatory service with high energy-density storage (70 kJ/m^3). The capacitor modules also contain eighty GE GL-37248 ignitrons which serve as triggered switches: forty to discharge the capacitors (functioning as S1 of Figure 2) and forty as electronic crowbars (functioning as S2 of Figure 2) to trap the energy in the driving-coil pair. The typical output shock response is given in Table I.

Table I. EDESS-1 Shock-Pulse Capability & Parameters

Shock pulse (peak)	150 g's
Payload mass	2000 kg
Shock duration (base width)	<4 ms
Shock pulse risetime	300 μs
Payload velocity change (max)	1.3 m/s
Payload displacement (max)	80 mm
Capacitor bank: 40 ea 15μF@ 20 kV	120 kJ
Driving coils: 380 mm dia 2 ea	54 μH

EDESS-2 and 3

Effort is now underway to assemble EDESS-2 which will have a 5 metric ton payload capability. The top and side views of the driving platform are shown in Figure 5. Generally the system will look very similar to EDESS-1. The number of capacitor modules (not shown) will be doubled to store 240 kJ although a tripling in size would have been desirable. Additional capacitor banks are available but competition for their use is keen. The reaction mass will be tripled to around 30 metric tons and the number of 380 mm diameter driving pairs, which were used successfully on EDESS-1, will be increased to 4. Computer-aided analysis shows that extending the number of driving pairs to 4 will keep the overall energy transfer efficiency nearly the same as in EDESS-1. The 4 coil-pair system will also provide some shock-pulse risetime adaptability by allowing coils to be connected in various series/parallel ways. Computer analysis also predicts that a range of shock pulse capabilities are possible.

To extend the payload capability of an electromagnetically-driven shock platform into the 15 to 30 metric ton range requires a departure from the use of capacitor banks as primary energy sources. This is primarily because the capacitor banks required would occupy very large spatial volumes and consequently not be portable. Homopolar generators exhibit high energy-density storage (350 kJ/m^3) and are capable of storing 10 to 20 MJ. Machines like this are being considered as replacements for capacitor banks in EDESS-3 to achieve the larger payload capability. A demonstration experiment (Figure 6),to shock-pulse a 15 metric-ton armor-plate payload using Weldon's 9 MJ homopolar generator [4] at the University of Texas is being planned.

Several important mechanical and shock control advantages accrue from this approach. The driving coils of EDESS-1 and 2 can be replaced by simple flat driving plates because the equivalent electrical capacitance of the homopolar generator is so large (5600 farads for the 5 megajoule homopolar). Also the risetime of the output shock profile can be varied easily by simply changing the applied magnetic field across the rotor. That this is true can be readily seen by noting that the voltage developed across the terminals of a homopolar generator is proportional to the applied magnetic field, Φ. For a constant stored energy in the homopolar of $\frac{1}{2}$ $C_H V^2$, the equivalent homopolar

capacitance, C_H, varies as $1/V^2$ and thus as $1/\Phi^2$. Since the shock pulse risetime, τ, from equation (1) varies roughly as T/4,

$$\tau \sim \sqrt{LC_H} \sim \sqrt{\frac{L}{\Phi}}$$

This means that the shock pulse risetime can be controlled by varying Φ, i.e. the greater Φ, the sharper the shock onset. This appears to be an important control advantage which has heretofore not been possible on EDESS-1 and 2. Peak shock levels can also be controlled without changing the relative shape of the output shock profile by simply changing the angular speed, ω, to which the homopolar generator is originally spun. These features are currently being studied in the design of the EDESS-3 generator.

Conclusions

The present experiments with the EDESS-1 prototype clearly demonstrate the feasibility of using electrical pulse power for generating explosive-like shocks in 1.0 and 2.0 metric ton payloads. The key to obtaining reliable shock performance lies in developing reliable and efficient driving-coil pairs. A considerable range of output shock profiles and payloads appears possible using capacitor banks as primary energy storage devices as will be tested with EDESS-2. Homopolar-powered systems appear promising for larger payload shock-testing applications where high efficiency, simplicity and compactness are important aspects. This effort has been sponsored by the Naval Surface Weapons Center, the Naval Sea Systems Command and the Defense Nuclear Agency.

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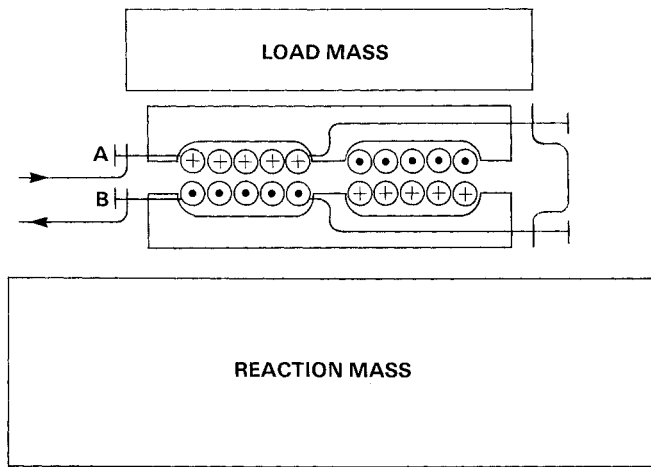
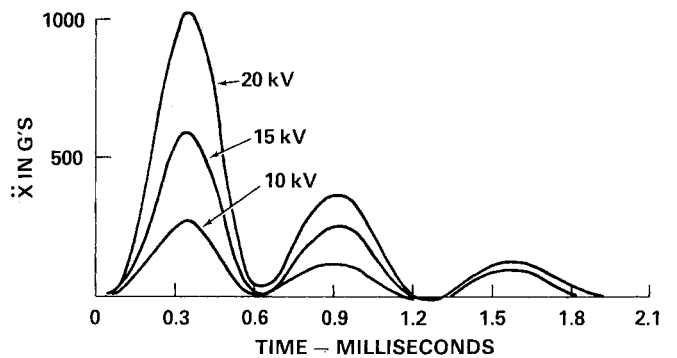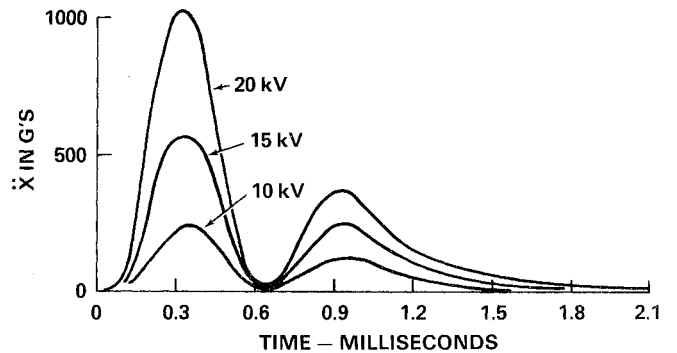FIGURE 1 SHOCK-GENERATOR CONCEPT:
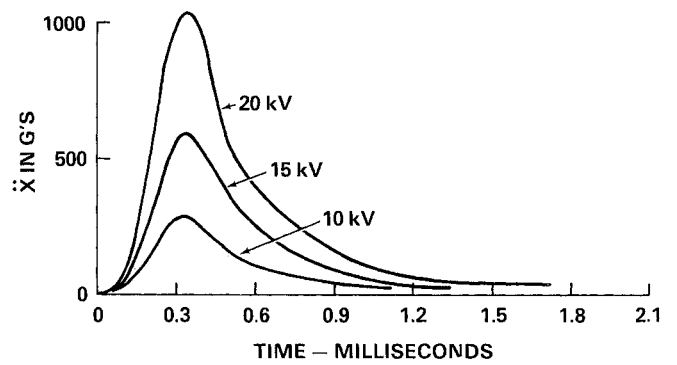REPULSIVE COIL-PAIRS

FIGURE 2 SHOCK-GENERATOR ELECTRICAL
EQUIVALENT CIRCUIT

FIGURE 3 PREDICTED SHOCK PROFILES FOR EDESS-1

EDESS-1 SHOCK GENERATOR
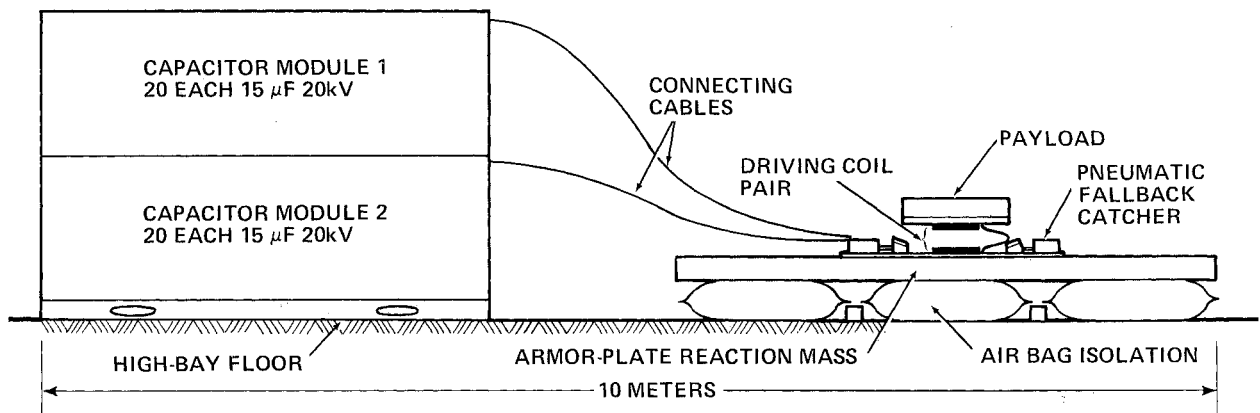
FIGURE 4 EDESS-1 GENERATOR: 2 METRIC TON
PAYLOADS

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CONNECTOR BLOCK

CROWBAR SWITCH

15" DIA DRIVING COILS

MASS (16 TONS)

SPRAG CLUTCHES, 4EI

TOP VIEW

PAYLOAD

SIDE VIEW
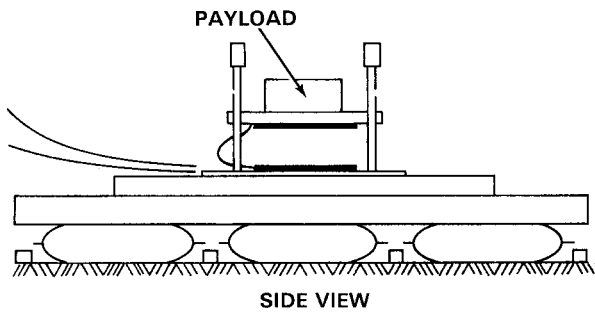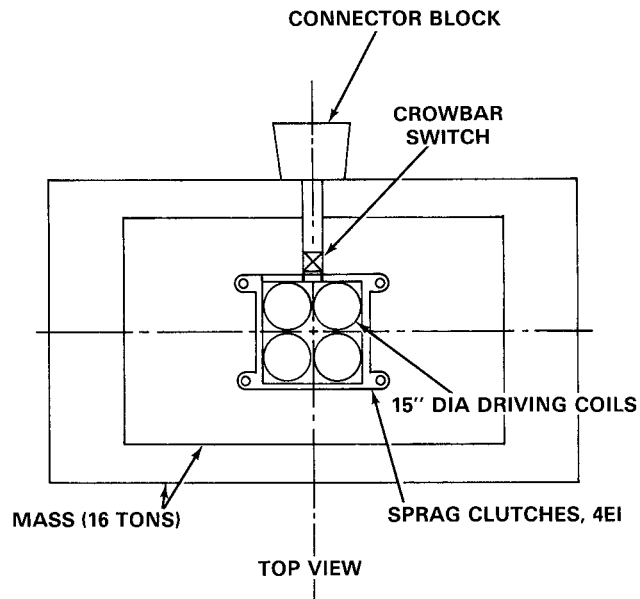
FIGURE 5 EDESS-2 GENERATOR: 5 METRIC TON PAYLOADS
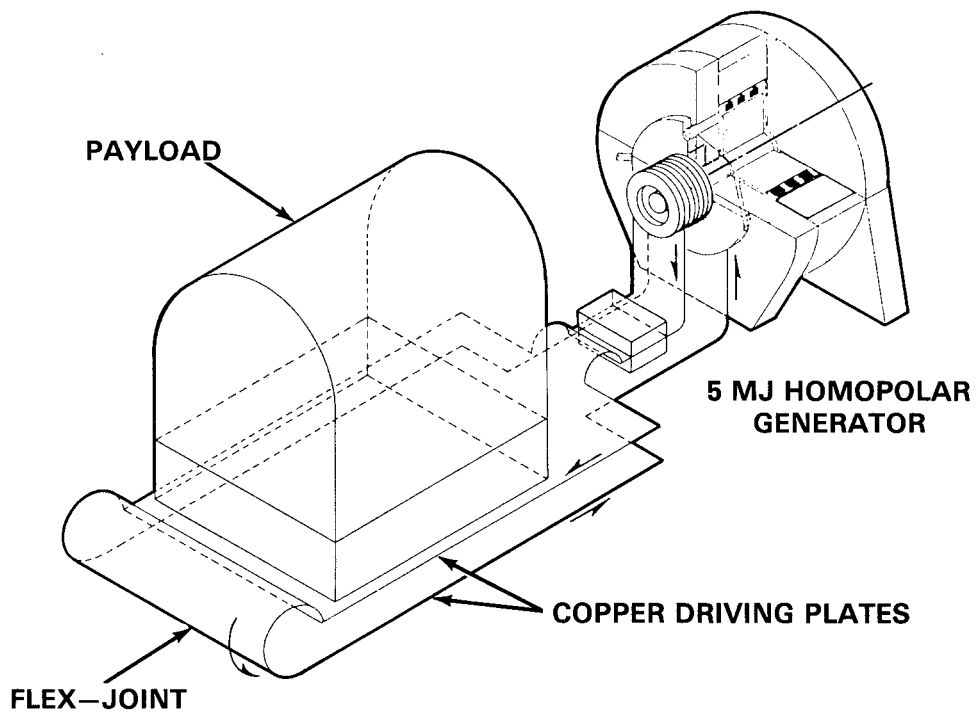

PAYLOAD

5 MJ HOMOPOLAR GENERATOR

COPPER DRIVING PLATES

FLEX—JOINT

FIGURE 6 EDESS-3: 15.0 METRIC TON PAYLOADS

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